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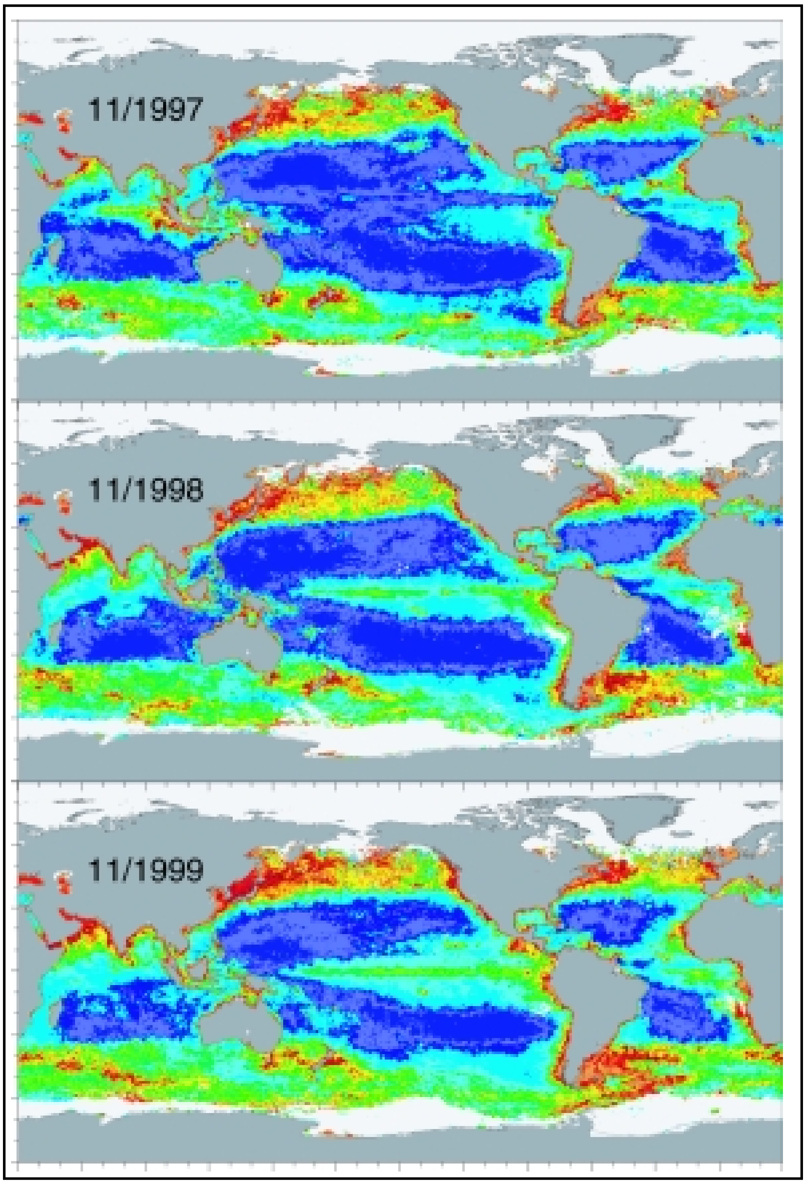
NASA/GSFC Research Activities for the Global Ocean Carbon Cycle: A Prospectus for the 21st Century

W.W. Gregg, M.J. Behrenfield, F.E. Hoge, W.E. Esaias, N.E. Huang, S.R. Long, and C.R. McClain



A contribution by the
Ocean Carbon Science Team
of the NASA/GSFC
Laboratory for Hydrospheric Processes
to the NASA/GSFC Task Force for Carbon

February 2000

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Space Administration

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Greenbelt, Maryland 20771

February 2000

Cover: SeaWiFS chlorophyll data for November 1997, 1998, and 1999. November 1997 shows depressed chlorophyll concentrations resulting from the 1997–1998 El Niño. Increased concentrations in 1998 and 1999 are the result of increased upwelling from La Niña conditions. The dramatic interannual variability shown here has important effects on global carbon fluxes. The 1997 El Niño suppressed outgassing of carbon dioxide in the tropical Pacific, which reduced estimated ocean uptake by 35%.

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FOREWORD

It is increasingly recognized that anthropogenic activities may have significant impacts on the Earth's climate. At issue is the concern that carbon dioxide emissions of industrial origin may alter the natural variability of the coupled climate system, with potentially devastating consequences in terms of climate change and habitability. In response to these concerns, the international community, including science and government components, has mobilized to address the scientific understanding of the global carbon cycle and ramifications of anthropogenic influence. The Kyoto accords and a series of reports by the Intergovernmental Panel on Climate Change are two distinct examples of the seriousness of these issues in the world community. The global ocean contains more than 90% of the nongeological active carbon on the Earth, and plays a key role in the coupled climate system. Thus understanding how carbon flows in the marine environment is critical to improving our understanding of the global carbon cycle and impacts on climate.

This document represents the contribution of a core of ocean scientists at the NASA/Goddard Space Flight Center to bring their expertise and the unique capabilities of NASA remote sensing to bear on this pressing issue. The formation of the Ocean Carbon Science Team provides focus and coordination of activities to improve our understanding of the ocean carbon cycle by maximizing the use and planning of ocean remote sensing. In this capacity, the Ocean Carbon Science Team is part of a larger NASA/GSFC Task Force for Carbon that combines and coordinates ocean, terrestrial, and atmosphere efforts in this regard. The specific activities exemplify a dedication of individuals to contribute to an issue of national and international importance, so that governmental policy may be guided by the light of scientific knowledge.

I wish to thank Watson Gregg and co-authors for their efforts in preparing this prospectus of present and planned research activities within the Goddard Laboratory for Hydrospheric Processes targeted at the global ocean carbon cycle.

Antonio J. Busalacchi
Chief, Laboratory for Hydrospheric Processes
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Greenbelt, Maryland

ABSTRACT

There are increasing concerns that anthropogenic inputs of carbon dioxide into the Earth system have the potential for climate change. In response to these concerns, the GSFC Laboratory for Hydrospheric Processes has formed the Ocean Carbon Science Team (OCST) to contribute to greater understanding of the global ocean carbon cycle. The overall goals of the OCST are to: 1) detect changes in biological components of the ocean carbon cycle through remote sensing of bio-optical properties, 2) refine understanding of ocean carbon uptake and sequestration through application of basic research results, new satellite algorithms, and improved model parameterizations, and 3) develop and implement new sensors providing critical missing environmental information related to the oceanic carbon cycle and the flux of CO_2 across the air-sea interface.

The specific objectives of the OCST are to: 1) establish a 20-year time series of ocean color, 2) develop new remote sensing technologies, 3) validate ocean remote sensing observations, and 4) conduct ocean carbon cycle scientific investigations directly related to remote sensing data, emphasizing physiological, empirical and coupled physical/biological models, satellite algorithm development and improvement, and analysis of satellite data sets.

These research and mission objectives are intended to improve our understanding of global ocean carbon cycling and contribute to national goals by maximizing the use of remote sensing data.

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AOL—Airborne Oceanographic Lidar

AVHRR—Advanced Very High Resolution Radiometer

CDOM—Chromophoric Dissolved Organic Matter

CZCS—Coastal Zone Color Scanner

EOS—Earth Observing System

ERB—Earth Radiation Budget

FEDS 98—Flux Exchange Dynamics Study

FRRF—fast-repetition-rate fluorometer

IOP—inherent optical property

ISCCP—International Satellite Cloud Climatology Project

MLL—Mixed Layer Lidar

MODIS—Moderate Resolution Imaging Spectrometer

NGTFC—NASA/GSFC Task Force for Carbon

NOAA—National Oceanic and Atmospheric Administration

NPOESS—National Polar-orbiting Operational Environmental Satellite System

NPP—NPOESS Preparatory Project

NSIPP—NASA Seasonal-to-Interannual Prediction Project

OGBM—Ocean General Biogeochemical/radiative Model

OGCM—Ocean General Circulation Model

OCST—Ocean Carbon Science Team

SeaWiFS—Sea-viewing Wide Field-of view Sensor

SEI—Special Events Imager

SiB2—Simple Biosphere model

SIMBIOS—Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies

SP_P&P—Short Pulse Pump and Probe lidar

SQM—SeaWiFS Quality Monitor

TCB—Total Constituent Backscattering coefficient

WFF—Wallops Flight Facility

1. INTRODUCTION

The final decades of the 20th century marked the emergence and rapid escalation of public and scientific concern that the environmental impacts of human activities have transitioned from the local to the global scale. At the forefront of these environmental issues has been the potential for global climate change resulting from rising atmospheric concentrations of carbon dioxide and other "greenhouse" gases. These concerns over global warming have led to an accelerated research focus on quantifying carbon exchange rates between the atmosphere and biosphere. Consequently, our understanding of sources and sinks of carbon has advanced enormously, but remaining uncertainties limit the forecasting capabilities of global climate models.

The document, A U.S. Carbon Cycle Science Plan, (Sarmiento and Wofsy, 1999) has been prepared by the Carbon and Climate Working Group to direct climate related research during the new millennium. An underlying theme of this document is that an accurate assessment of future global climate change requires a coordinated, interagency research strategy with an overall scientific contribution that is greater than the sum of its parts (Sarmiento and Wofsy, 1999). The research program described in the following pages represents a contribution by Goddard's Ocean Carbon Science Team (OCST) toward this larger, interdisciplinary effort. This research program is intimately related to and dependent upon the broader activities of the NASA/GSFC Task Force for Carbon (NGTFC), as well as the external efforts of the scientific community as a whole.

Sarmiento and Wofsy (1999) identified two overarching goals of the U.S. Carbon Cycle Science Plan:

1. Identify the fate of anthropogenic carbon dioxide that has already been emitted.

2. Assess future atmospheric carbon dioxide concentrations resulting from past and future emissions.

Accomplishing these tasks requires accurate quantification of carbon fluxes among the oceans, land, and atmosphere. Sources and sinks for carbon are both biological and chemical in nature. By far the largest reservoir of carbon is sedimentary carbonates (order: 1022 g), but it is the far smaller mobile reservoirs, distributed among the oceans, land, and atmosphere that are critical to changes in global climate.

Currently, the most accurately constrained carbon flux in global climate models is that released annually from fossil fuel combustion [order: 5.5 ± 0.5 x 1015 g = 5.5 Petagrams (Pg)]. The net annual increase in atmospheric CO_2 is also well quantified at 3.3 ± 0.2 Pg, leaving a difference of 2.2 Pg y-1 that can be attributed to oceanic and terrestrial carbon sinks (Sarmiento and Wofsy, 1999). Of these two, it is thought that the oceanic sink is most accurately defined, with an annual uptake of approximately 2.0 ± 0.8 Pg (Sarmiento and Wofsy, 1999). It is important to note, however, that models primarily attribute oceanic carbon uptake to abiotic, physical-chemical processes affecting the solubility pump, while the role of biotic, photosynthetically driven pathways remain largely neglected. The effective terrestrial carbon sink is the most poorly resolved component of the global carbon cycle, with estimates ranging over a factor of two. In fact, terrestrial carbon storage is typically estimated through simple mass and/or flux balance with the atmosphere and ocean budgets (Sarmiento and Wofsy, 1999). Based on such mass/flux balance considerations and assuming a terrestrial carbon source of 1.6 ± 1.0 Pg y-1 from deforestation and land use change, the maximum potential terrestrial carbon sink is estimated at roughly 1.8 ± 1.6 Pg y-1.

The preceding overview represents current model estimates of global carbon fluxes. It identifies a "missing" carbon sink of roughly 1.8 Pg y-1 that is often attributed to the terrestrial component, but also involves oceanic mechanisms entirely ignored in the models. Whatever the mechanisms, increased CO_2 emission during the industrial revolution implies the "missing sink" has been stimulated, either directly or indirectly, by increased atmospheric CO_2 concentrations. Evidence is now mounting that terrestrial carbon sequestration in the Northern Hemisphere has increased during the last century due to a lengthening of the growing season, but the magnitude of this phenomenon remains controversial. Limits on such terrestrial carbon sinks are directly dependent upon the accuracy with which oceanic uptake has been estimated. From the mass/flux balance approach, omission of any important oceanic processes directly increases or decreases the potential size of the terrestrial sink.

Achieving closure on the contemporary global carbon budget will lend credibility to model predictions of future atmospheric CO_2 concentrations, but requires refined descriptions of important carbon pathways and feedbacks. Sarmiento and Wofsy (1999) detailed in their U.S. Carbon Cycle Science Plan a wide variety of field measurements that will contribute such information toward improved model parameterizations. This approach is essential to improve the fundamental understanding of processes, but is inadequate to provide a large-scale view of carbon cycling. Spatial and temporal variability on global scales is so large as to preclude simple extrapolation from these point-source measurements. Remote sensing data, although they may lack the accuracy of the field measurements, can provide observations and context of the large-scale variability.

Rigorous integration from these small-scale, mechanistic studies to global fluxes is critically dependent upon large-scale, remotely sensed observational data.

The error associated with integrating point-source field measurements to global scale processes would be prohibitive to any efforts at balancing the global carbon budget without remote sensing data. Availability of satellite-derived observational data on crucial atmospheric and biospheric variables is critical for contributing credibility to global models. These data capture the wide range of spatial and temporal variability, and provide the necessary input fields for process-oriented approaches, present a vehicle for assessing model performance, and frequently lead to the discovery of unanticipated feedbacks within the biosphere. Consequently, the fundamental and decisive contribution of the OCST is to develop and maintain long-term, internally consistent global scale observations of critical environmental variables and to conduct basic and applied research relevant to the integration of small-scale mechanisms into global scale processes.

Development of the NGTFC represents an initiative to establish a Center of Excellence in interdisciplinary global carbon research. This initiative will entail the cooperative interaction of terrestrial, oceanic, and atmospheric scientists linked through the common interest of improving global carbon flux estimates through the application of remote sensing data and tied to the greater scientific community through panel oversight and evaluation. The inherent interdependence of the ocean-atmosphere-land system lends naturally to the establishment of such an interdisciplinary science program. A multitude of feedbacks exists between the mobile carbon reservoirs, such as the stimulation of photosynthetic carbon uptake by atmospheric CO_2 enrichment, enhanced coastal productivity supported by agricultural fertilization practices, and altered oceanic CO_2 uptake resulting from iron-induced changes in nitrogen fixation and photosynthesis caused by climate-induced alterations in terrestrial desertification patterns. Any effective evaluation of these processes requires the joint effort of scientists with a diversity of expertise, which is precisely the underlying motivation for the NGTFC.

A full description of the ensemble of research activities to be conducted under the NGTFC is beyond the scope of this document. Rather, we have limited the current project overview to measurements and research activities directly related to oceanic carbon cycling processes. It must be kept in mind, however, that these activities represent a contribution from the OCST toward the greater objectives of the NGTFC. It is also important to recognize that neither NASA nor any other single agency can alone satisfy all the requirements for a major improvement in the characterization of the global carbon cycle, but rather that the efforts of the OCST represent a contribution to the overall goals of the scientific community.

1.1 Carbon Cycling in the Global Oceans

Carbon cycling through the terrestrial component of the biosphere is intuitively easy to understand, due to our personal experiences of breathing air, cultivating the soil, seeing plants grow and die, and watching leaves emerge each spring, fall each autumn, and eventually decompose. For most people, carbon cycling processes in the oceans are far more obscure.

The oceans interact with the atmosphere through the air-sea interface, with CO_2 either entering or leaving the ocean depending upon its concentration relative to equilibrium with the overlying air (ΔpCO_2) and the sea state. This ΔpCO_2-dependent gas exchange is termed the "solubility pump" and it is influenced both by physical-chemical processes and biological activity. Photosynthetic carbon fixation by phytoplankton functions as the primary link between ocean biology and the solubility pump (figure 1).

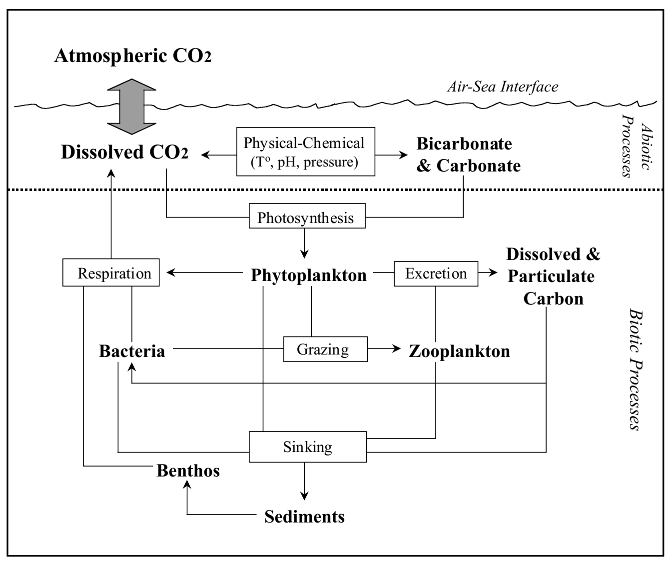

Figure 1. Pathways in the ocean carbon cycle.

Photosynthesis represents an oceanic carbon sink, as it decreases the partial pressure of CO_2 near the ocean surface and consequently increases the potential flux of CO_2 from the atmosphere through the air-sea interface, depending upon processes occurring at the boundary. Eventually, most of the organic material formed through photosynthesis is degraded back to CO_2 through respiratory processes in the water column (figure 1).

Respiration thus represents a CO_2 source to the atmosphere. The net effect of photosynthesis and respiration on oceanic carbon uptake, commonly referred to as the “biological pump,” is spatially and temporally dependent. It functions through changes in carbon stored in sedimentary, dissolved, and particulate pools (figure 1). Over geologic time scales, photosynthetic CO_2 uptake has exceeded respiratory CO_2 emission to the extent that >95% of the sedimentary carbon reserves on Earth are of oceanic origin. At shorter time scales, the balance between photosynthesis and respiration is less well understood and is the source of great uncertainty in model estimates of the ocean carbon budget.

Fundamental processes of photosynthesis and respiration are similar between ocean and land plants, but carbon cycling differs dramatically in these two systems due to contrasting turnover rates of plant biomass. Plant biomass in the oceans represents less than 0.2% of the biospheric total, but contributes 50% of the annual net primary production on Earth (Field et al. 1998). Consequently, the global phytoplankton biomass on average turns over every 2–6 days, whereas in terrestrial systems turnover rates are on the order of decades to centuries depending on community composition (e.g., forest ecosystems versus grasslands). Thus ocean biological systems can respond to environmental changes much more rapidly than land systems.

In terrestrial systems, understanding sources and sinks of carbon requires quantification of carbon storage and fluxes through leaves, woody materials, and soils. In the oceans, quantifying biologically mediated carbon sources and sinks requires an understanding of fluxes from the illuminated surface layer to the deep ocean and the fate of organic material recycled throughout the water column. Some carbon remains in particulate form, which can settle to the bottom and represent a loss to the Earth carbon system. Some is stored as dissolved organic carbon (DOC), whose recycling pathways are poorly understood. DOC in the ocean comprises the largest reservoir of organic matter in the sea and is comparable in size to the reservoir of organic matter in soils of the terrestrial biosphere (Ducklow et al., 1995) and to the amount of carbon in the atmosphere, 750 PgC (Wiebinga and de Barr 1998; Williams, 1975). The relative importance of various carbon pathways is dependent upon regional differences in ecosystem structure, such that upwelling areas tend to be dominated by diatoms and other large species that contribute a sinking particulate flux, while stratified central ocean regions are generally fueled through microbial recycling processes within the surface mixed layer.

Contrary to earlier assumptions, it is now clear that the ocean carbon cycle is not in steady state (Falkowski et al., 1998). The dynamic nature of ocean circulation and biological processes insures an oceanic response to global climate change that may very well already be engaged. Quantifying the magnitude of this response and defining the mechanisms involved will require a substantial, long-term investment by NASA into the development and operation of airborne and satellite technologies, along with basic research focused on linking large-scale remotely sensed environmental data to carbon cycling processes.

The OCST at NASA Goddard will play a pivotal role in satisfying the scientific and technical requirements for an improved understanding of carbon cycling in the oceans. Central goals of the OCST research program are to:

1) detect changes in biological components of the ocean carbon cycle through remote sensing of bio-optical properties;

2) refine understanding of ocean carbon uptake and sequestration through application of basic research results, new satellite algorithms, and improved model parameterizations;

3) develop and implement new sensors providing critical missing environmental information related to the oceanic carbon cycle and the flux of CO_2 across the air-sea interface.

Remote sensing technologies previously developed by NASA/GSFC have already had an enormous impact on our understanding of carbon fluxes through the ocean. For example, derived global chlorophyll fields based on the CZCS and SeaWiFS ocean color sensors have led to net ocean carbon fixation estimates being revised from < 28 Pg C y-1 to > 50 Pg C y-1 (Behrenfeld and Falkowski, 1997; Field et al., 1998; Iverson et al., 2000). The CZCS has also been used to derive dissolved and particulate organic carbon fields in terms of the oceanic absorption coefficient (Hoge et al., 1995). These estimates will continue to improve with the availability of new ocean color data. The OCST research program will contribute indispensable information toward achieving the goals of the U.S. Carbon Cycle Science Plan.

Goddard’s OCST has been instrumental in ocean color research and operations for virtually every mission that has flown, nationally and internationally. The expertise built by the OCST over the years in ocean color is unsurpassed. Sarmiento and Wofsy (1999) and NASA (1999) have established that continuous observations of ocean color are crucial for improving our understanding of the ocean carbon cycle. As the NASA Center for Excellence in Earth Sciences, the Goddard OCST must play a lead role in the refinement of carbon cycle understanding through the use of remote sensing. Enhanced support for the activities of the Goddard OCST provides the only practical means for fulfilling NASA's commitment to the US Carbon Cycle Science Plan.

The Goddard OCST has developed an approach to accomplishing our three primary goals (above). The central objectives of this research are to:

1) establish a 20-year time series of ocean color;

2) develop new remote sensing technologies;

3) validate ocean remote sensing observations;

4) conduct ocean carbon cycle scientific investigations directly related to remote sensing data.

We believe that the scientific contribution of this research to the understanding of global carbon cycling will further establish NASA Goddard Space Flight Center as a continuing world leader in Earth system sciences.

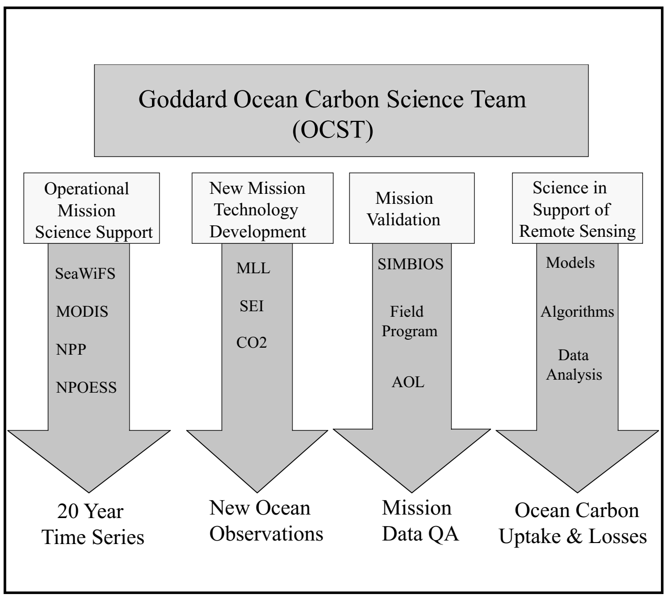

Figure 2. Primary objectives and functions of the GSFC Ocean Carbon Science Team.

2. OBJECTIVES

2.1 20-year Time Series of Ocean Color

Continuous global observations of ocean color are the cornerstone of NASA's contribution to a national carbon cycle initiative. The absolute necessity of a multidecadal time series of ocean color and related observations was specifically stated in the U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999). A 20-year time series is crucial for documenting and understanding long-term changes in carbon-related ocean processes (Kaufman et al., 1998). A 20-year time series enables us to understand decadal-scale trends in the presence of the larger signal provided by interannual variability (e.g., El Niño and La Niña), just as interannual variability requires multiple years to distinguish it from the larger-still signal resulting from seasonal variability. The 20-year time series will be our first evidence of longer-term trends that are invisible at smaller time scales, and are crucial to understanding global change. Thus, insuring availability of continuous remote sensing data is of the highest priority for NASA's ocean carbon cycle research (NASA, 1999).

An important difference between terrestrial carbon cycle research and ocean studies is the stark difference in dedicated remote sensing missions. Variability in terrestrial plant biomass has now been monitored remotely and continuously for nearly 20 years, whereas representative coverage of oceanic plant biomass has only been available for 2 years. The first ocean color sensor, the Coastal Zone Color Scanner (CZCS), provided a proof-of-concept demonstration that such observations are scientifically feasible and, in fact, represents an essential method for observing spatial distributions in living marine constituents. However, lack of temporal coverage severely limited the utility of CZCS data for quantifying global annual carbon fluxes and its variability (figure 3). The new Sea-viewing Wide Field-of-view Sensor (SeaWiFS) provides our first systematic, routine global observations of chlorophyll distributions (figure 3). This sensor, operating now for 2 years, represents the beginning of a comprehensive time series of global ocean color data.

Scheduled future NASA missions involving ocean color measurements include the Moderate Resolution Imaging Spectrometer (MODIS) on the Earth Observing System (EOS) Terra and Aqua platforms, the NPOESS Preparatory Project (NPP), and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) (table 1). The Goddard OCST will provide personnel, expertise, and advocacy to help these missions be supported and flown. Specific responsibilities of the OCST include: 1) scientific oversight of sensor design to meet the requirements of first-class science observations, 2) scientific oversight of mission design to meet observational requirements, 3) mission simulation activities to evaluate alternatives and trade-offs in sensor/mission design, and 4) assurance that data are processed with state-of-the-art scientific methods and made freely available to the public in a timely manner.

OCST personnel have established a first-rate mission support capability that has been instrumental in virtually every ocean color mission flown to date, both nationally and internationally. Efforts in sensor calibration (McClain et al., 1998; Barnes et al., 1999; Gregg et al., 1999), mission analysis (Gregg and Patt, 1994; Gregg,

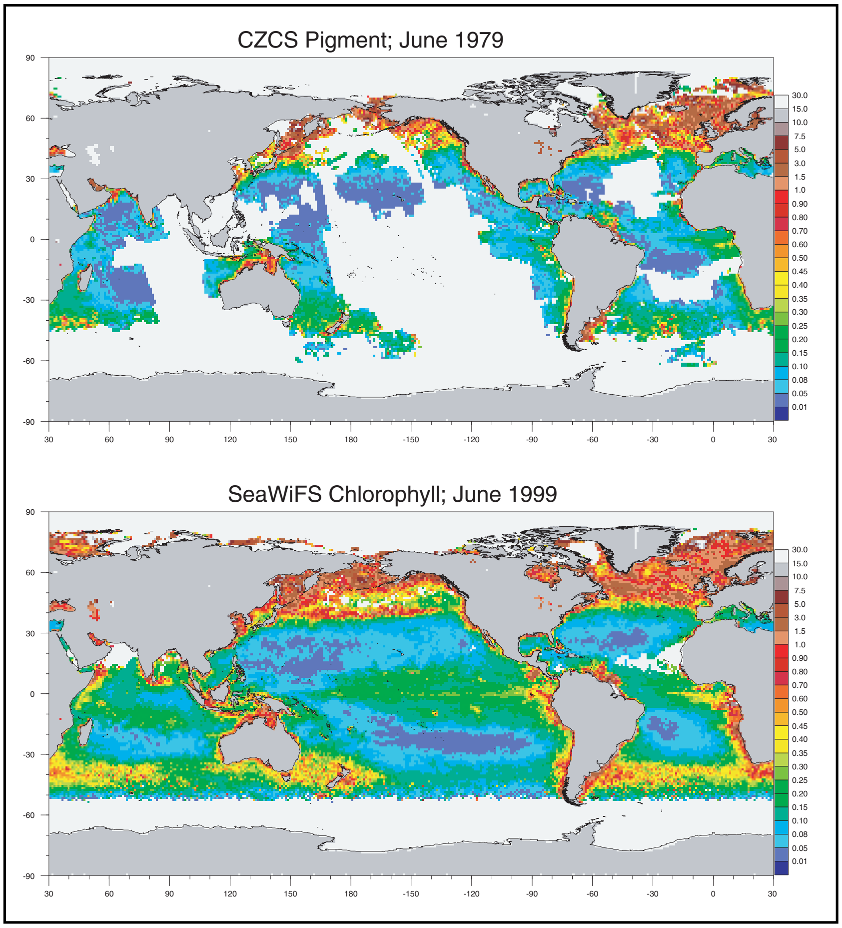

Figure 3. Coverage by the CZCS in June 1979 compared to the routine global operational coverage provided by SeaWiFS, as shown for June 1999, 20 years later.

Table 1. Ocean color missions planned for the next decade

1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008

SeaWiFS -- >

EOS-Terra ---------------------------->

EOS-Aqua ----------------------->

NPP ------------------------------------->

------>
NPOESS

1999), navigation (Patt and Gregg, 1994; Patt et al., 1997), full mission simulation (Gregg et al., 1997), data processing (Feldman et al., 1989, and the SeaWiFS, CZCS, Ocean Color and Temperature Scanner (OCTS), and MOS data archives), and mission management (SeaWiFS) have fully demonstrated that the Goddard OCST is unsurpassed in ocean color mission development, design, and operation.

The 20-year time series of ocean color data requires a dedicated effort to ensure data compatibility across missions. This is a new area for ocean color with its relatively short data archive, but problems have occurred in other long-term mission sequences, such as the Advanced Very High Resolution Radiometer (AVHRR), Earth Radiation Budget (ERB), and International Satellite Cloud Climatology Project (ISCCP) series. In the limited ocean color experience, CZCS visible bands degraded by as much as 50% over the lifetime of the mission while the near-infrared (NIR) bands remained relatively stable (Evans and Gordon, 1994). On the other hand, most of the degradation in SeaWiFS is in the NIR bands (Barnes et al., 1999). These changes, if not identified and characterized, can produce very misleading trends in the derived products from mission to mission. Data compatibility is an issue that transcends individual mission responsibilities, but is required for the scientific usefulness of the time series. The OCST will ensure, through its Mission Validation activity and with its expertise, a compatible mission-to-mission time series of ocean color data.

2.2 Develop New Remote Sensing Technologies to Improve Our Understanding of Ocean Carbon Cycle Issues

Ocean color is the centerpiece for the OCST contribution to a national carbon science initiative. However, just as the collective contribution of all agencies to carbon cycle research pushes the science further than the sum of its parts, the simultaneous observation of multiple marine environmental variables provides far greater insight into carbon cycling than ocean color alone. For example, a first step toward quantifying the "biological pump" is to assess the rate of photosynthetic carbon fixation. Conversion of remotely sensed chlorophyll or phytoplankton absorption coefficient fields to photosynthetic rates requires assessment of physiological variability and the photodecomposition rates and spectral absorption properties of the underlying organic pool, which in turn are related to additional environmental fields, such as temperature, mixed layer depth, clouds, and nutrients. Further improvement in the understanding of the solubility pump requires information on surface roughness regulating gas exchange across the air/sea interface, chemical reactions between dissolved CO_2 and bicarbonate in seawater, and the relative partial pressures of CO_2 in the surface mixed layer and the atmosphere.

New remote sensing technologies that permit direct observation of environmental variables influencing oceanic carbon cycling have the greatest potential for making breakthrough scientific contributions. As the agency that pioneered Earth remote sensing, NASA is uniquely positioned to play the lead role in development of such new technologies. This leading role will be supported by the expertise assembled within the OCST, which already includes extensive experience in all previous global missions flown and an appreciation for the intricacies of mission development and design. Development of high-impact, breakthrough technologies related to ocean carbon cycling requires four primary ingredients: 1) an intimate understanding of the fundamental processes involved, 2) first-class engineering, computing, and laboratory facilities promoting fundamental scientific advances that lead to new technologies, 3) extensive understanding of the physics of electromagnetic signal propagation through the atmosphere and oceans, and 4) free and open exchange of information with engineering or instrument scientists. Provided personnel expansion of the OCST, these ingredients can be satisfied by virtue of the group's extensive experience and proximity to the world class engineering workforce at GSFC.

Analysis of potential new missions is already underway within the OCST. Exciting new technologies currently being investigated include a Special Events Imager (SEI), a Mixed Layer Lidar (MLL), an airborne short pulse Pump and Probe (SP_P&P) lidar, and a CO_2 lidar. The SEI is a proposed joint NOAA/NASA mission to provide new and refined information on coastal processes, including carbon cycling. Coastal regions are of particular national interest because of their predominant influence on U.S. fisheries catches, as well as representing roughly 25% of the total ocean carbon fixation (Walsh, 1988) and contributing approximately 60% of the particulate carbon flux to the sediments. Coastal regions, however, have their own suite of unique challenges with respect to remote sensing measurements. Two important issues in coastal regions are the effects of chromophoric dissolved organic matter (CDOM) on ocean color estimates and the influence of diurnal phytoplankton growth cycles and loss terms on synchronous observations obtained from operational missions. Tidal cycles can cause polar orbiter data to be highly aliased, resulting in erroneous estimates of carbon fluxes between land and ocean via rivers and estuaries (to the extent of even giving the incorrect sign to the flux!). The high temporal coverage provided by the SEI will yield important information to address these issues.

The MLL is another particularly exciting new technological effort. The MLL uses lidar techniques to determine the depth of maximum suspended particulate concentration. This maximum, often referred to as the "deep chlorophyll maximum," generally lies just below the surface mixed layer. Remote sensing data on mixed layer depths provides information on the vertical dimension of the water column (which is unavailable from passive optical techniques) and has many important applications related to carbon cycling, for example:

1) The mixed layer depth affects ocean circulation and the exchange of CO_2 and heat between the ocean and the atmosphere.

2) The relationship between surface chlorophyll concentration and phytoplankton carbon fixation is a function of solar angle, cloudiness, mixed layer depth, and the rate of light attenuation through the water column.

3) A positive rate of net primary production for the water column is dependent on the relationship between euphotic depth and mixed layer depth.

Data retrieved from the MLL will also help clarify the relationship between ocean color observations of surface biomass and its depth distribution.

Ongoing OCST research that is directly applicable to new phytoplankton-carbon products is an airborne laser research into the development of algorithms for satellite retrieval of the photosynthetic parameters, thereby improving the phytoplankton-carbon product.

In parallel with this research, a Rutgers University-NASA funded project is also underway to develop alternative/complementary techniques for remotely observing variable fluorescence parameters. This effort is functionally an upscaling of the very successful fast-repetition-rate fluorometer (FRRF), such that similar information can be obtained from remote sensing platforms. The FRRF measures functional absorption cross sections of photosystem II, photochemical quantum yields, and electron turnover rates through the light reactions, all of which are fundamental parameters related to photosynthetic carbon fixation. It is highly recommended that this important research be continued and augmented.

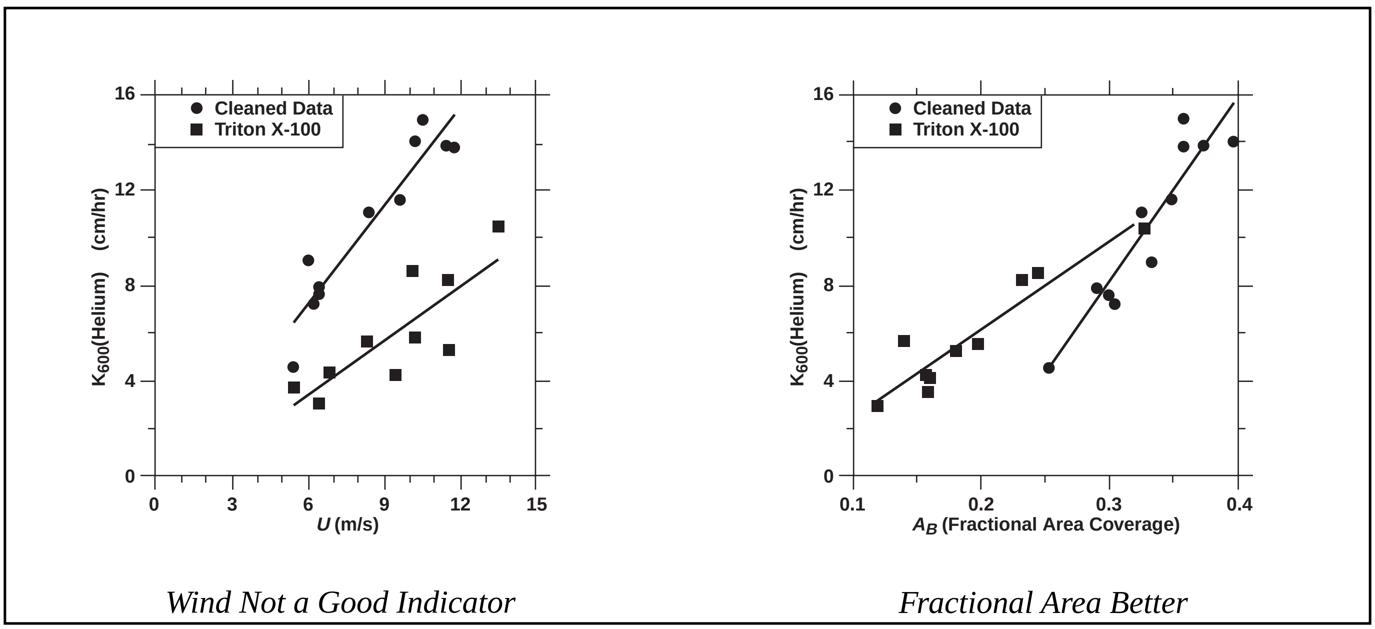

Figure 4. Relationship between gas exchange between the ocean and atmosphere as a function of wind speed (left) and fractional area coverage by whitecaps (right).

pump-and-probe technique whose feasibility has only recently been demonstrated (Chekalyuk et al., 1999; Wright et al., 1999). This airborne dual-laser (SP_P&P) lidar system allows wide area determination of photosynthetic parameters near dusk and during early morning hours before solar effects are induced. The system also allows concurrent retrieval or inference of chlorophyll and phycoerythrin pigment biomass, both normalized by the concurrent laser-induced water Raman backscattering spectral line. The contemporaneous use of an airborne passive oceanic radiometer also allows

In addition to the strictly ocean-oriented new technologies described above, a CO_2 lidar system is also being developed to measure atmospheric CO_2 concentrations remotely over land and oceans. This is a key component in understanding the potential for CO_2 fluxes between the oceans and atmosphere. Details regarding this technology are provided in the overall implementation plan for the NGTFC (C. Tucker et al. In prep.).

Exchange of CO_2 between the ocean and atmosphere is a critical, and poorly understood, aspect of ocean carbon cycling. Efforts to improve our understanding of these processes, and how to measure them, is essential to understanding the dynamic interchanges in the atmospheric and oceanic carbon pools.

Gas exchange between the ocean and atmosphere is dependent upon the sea state: the surface roughness, the spray and the whitecaps from the surface and trapped bubbles generated by breaking waves. Recent studies at out Observational Sciences Branch (FEDS.98, the Flux Exchange Dynamics Study) indicate that surface roughness is a much better parameter for quantifying the air-sea gas flux than the traditionally used wind speed (see, for example, Kraus and Businger, 1994).

As both the whitecap coverage and surface roughness can be measured by microwave sensors such as radiometers and scatterometers (see, for example, Rees, 1993), there is tremendous potential that improved algorithms can be developed to quantify the air-sea mass flux based on data from microwave remote sensing instruments. This will open up the possibility of global monitoring of the gas fluxes for the first time. This work can also potentially lead to new mission technologies to refine our observations of surface roughness, leading to better parameterizations of CO_2 fluxes.

The geophysical variables measured by the aforementioned new technologies cannot be obtained by any remote sensing technology currently available. Thus, despite the technological and scientific hurdles that remain, the potential rewards in terms of improved knowledge on key aspects of the global carbon cycle are enormous, but will require the dedicated effort of personnel in the OCST.

2.3 Mission Validation

The Goddard OCST Carbon Science Plan relies heavily on remotely sensed observations of key geophysical qualities. Validation of these data products is crucial for the success and usefulness of the 20-year time series of ocean color data, as well as for new mission technologies. The GSFC OCST has assumed a leading role in the international community for ocean color mission validation. This experience began with the CZCS and continues under the SeaWiFS, MODIS, and Sensor Intercomparison and Merger for Biological and Interdisciplinary Ocean Studies (SIMBIOS) programs.

The SIMBIOS and SeaWiFS Projects have established well-organized, globally diverse, and continuous field programs that provide essential sea truth data for comparison with satellite ocean color derived products. The SeaWiFS Project has addressed problems with field measurements through the SeaWiFS protocol development, calibration round-robin, and field observation programs (Hooker and McClain, 1999). These efforts are geared toward addressing measurement error, satellite validation, and related technology development. The SeaWiFS field program is focused and advanced in terms of observational accuracy and protocols development. All activities have been documented in the SeaWiFS technical memorandum series.

SIMBIOS is a collaborative effort with the external community to provide in situ observations that can be used to help intercompare ocean color observations from multiple scheduled and flying national and international missions. A fleet of sites distributed globally provides a diverse observational data set that can allow evaluation of ocean color mission performance in a variety of conditions (McClain and Fargion, 1999). Data are stored in a highly organized data base that can be accessed by all investigators for mission comparison and evaluation, thereby promoting collaborative validation efforts.

Effective mission validation also requires an understanding of the characteristics of the sensor. Aspects such as out-of-band response, polarization, scan modulation, scan geometry, focal plane design, stray light, and signal-to-noise, affect the derivation of ocean color products and must be understood in order to interpret the data. Experience gained with multiple sensors in the SIMBIOS effort has improved the capability of the OCST to validate new missions.

The OCST has pioneered innovative approaches to mission validation. The SeaWiFS Quality Monitor (SQM) was developed by OCST personnel in collaboration with the National Institute of Standards and Technology to enable high-precision tracking and monitoring of field radiometers used to validate ocean color data (Hooker and Aiken, 1998; Johnson et al., 1998). The SQM reduces variability of in situ radiometers and enables a consistent comparison to remote sensors. This in turn increases our ability to utilize in situ data to understand the calibration of the remote sensors and provide a greatly enhanced satellite data product. The OCST intends to provide equal capability for the 20-year ocean color time series and to develop similar methods and field support for new technologies.

Another capability of the OCST is the Airborne Oceanographic Lidar (AOL) program at Wallops Flight Facility (WFF). The AOL has both active (laser) and passive (solar) capabilities, and has been used for low-altitude aircraft underflights of SeaWiFS to (1) assist with evaluation of SeaWiFS radiometric performance and (2) develop oceanic radiative transfer-based algorithms for retrieval of (a) phytoplankton absorption coefficient, (b) CDOM-detritus absorption coefficient, and (c) total constituent backscattering coefficient (Hoge et al., 1999). Results suggest good agreement in general with SeaWiFS radiance data, which enhances confidence in the SeaWiFS data products. Since the AOL system flies below most of the atmosphere, it can be used in conjunction with satellite ocean color sensors to validate and develop atmospheric correction algorithms. The AOL will continue to play a critical role in evaluating MODIS oceanic and atmospheric performance, as well as future operational missions.

Methods for validation of phytoplankton absorption coefficient, CDOM absorption coefficient, and total constituent backscattering should initially mimic those used to validate pigment biomass (chlorophyll). Accordingly, airborne methods for retrieval of oceanic carbon will initially be comparable to those now in use for biomass. The highest priority for research and development is total constituent backscattering retrieval, since it is not now widely measured either aboard ship or airborne field experiments. Errors in total constituent backscattering models propagate into the CDOM absorption coefficient and phytoplankton absorption coefficient (Hoge and Lyon, 1996) and therefore cause errors in derived carbon fields.

2.4 Conduct Ocean Carbon Cycle Science Activities Directly Related to Remote Sensing

The scientific objectives of the OCST are:

2.4.1 develop and refine models that improve our estimates of ocean carbon fixation and interactions among carbon components and the physical environment;

2.4.2 develop new satellite-based algorithms to improve our knowledge of carbon cycle components and variability, and the air-sea gas flux;

2.4.3 analyze spatial and temporal variability of satellite data on regional and global scales over seasonal, interannual, interdecadal, and climate-change time scales.

2.4.1 Development and Refinement of Models

The OCST pursues scientific advancement on ocean carbon cycling issues using a variety of modeling approaches, including (1) physiological models based on analysis of fundamental physical and biological processes, (2) empirical satellite-based production models, and (3) large-scale numerical models that integrate physical and biogeochemical processes (i.e., "coupled" models). These approaches provide separate, complementary views of various carbon cycle processes. The OCST has demonstrated expertise in each of these research areas, which will be further expanded to enhance GSFC's contribution to the national carbon cycle goals. The three modeling approaches are all intimately linked to satellite data, which forms the primary contribution of the OCST: the physiological models require a diversity of global observations available from satellites to understand the principles involved, empirical models are directly forced by satellite data, and coupled models are actively constrained by satellite data. The ultimate goal of the OCST modeling efforts is to refine our understanding of carbon processes in the oceans so that we may eventually develop a capability to forecast changes in the ocean carbon cycle.

Physiological Models: "Photosynthesis models" and "coupled models" represent two fundamentally different approaches toward investigating carbon cycling through phytoplankton biomass. The latter functionally "grows" phytoplankton in the ocean based on modeled physical and chemical distributions. The former directly utilizes remote sensing data on phytoplankton chlorophyll fields and models the corresponding distribution of carbon fixation. These models estimate carbon fixation either using simple empirical relationships (see below) or by applying more basic concepts in phytoplankton physiology and ecology (i.e., "physiological" models).

Development of physiological models of phytoplankton photosynthesis dates back over 40 years (Talling, 1957; Ryther, 1956). Application of such models to global estimates of carbon fixation were severely limited until satellite remote sensing data of near surface chlorophyll fields became available. In anticipation of these upcoming satellite data products, a considerable effort was put forward in the mid-1970's to develop model parameterization based on chlorophyll. These efforts continued through to the current decade, with increasing emphasis placed on model parameterizations of photoacclimation (essentially, changes in chlorophyll per cell as a function of light intensity and spectra). Recently, we have provided strong evidence that classic photoacclimation is not the primary driver of variability in the ratio of carbon fixed per unit chlorophyll (Behrenfeld and Falkowski, 1997a,b). Rather, it appears that model improvements need to focus on the simultaneous effects of light limitation, grazing, and the nature and degree of nutrient stress.

An important aspect of the OCST modeling efforts is thus to define relationships between the physical/chemical attributes of the marine environment and physiological variability, integrate this information with satellite data fields, and produce new generations of ocean carbon flux estimates. From this point, additional models can be applied to estimate export carbon fluxes and carbon recycling pathways to better understand the magnitude of the biological pump and its removal of CO_2 from the atmosphere (figure 1).

Defining the required model relationships will involve field and laboratory studies directly related to satellite-based models. For example, one of the major breakthroughs in phytoplankton ecology during the later half of this century has been the demonstration of widespread growth limitation by iron (Coale et al., 1996, Behrenfeld et al., 1996, Behrenfeld and Kolber, 1998). Compared to other types of nutrient limitation or nutrient replete growth, iron limitation has a unique effect on the relationship between carbon fixation and chlorophyll, which can be traced to stochiometric changes in the ratio of photosytem II to photosystem I. Consequently, satellite data-based models of ocean carbon fixation must include appropriate parameterizations for iron-limited versus non-iron-limited regions. These relationships are yet to be defined, but will be pursued through laboratory and field studies. Defining the regions of iron limitation will also be a goal of the field measurements and based on a newly discovered diagnostic of iron limitation utilizing in situ variable fluorescence measurements (Behrenfeld and Kolber, 1998).

Basic research efforts will also be conducted to better define changes in carbon fixation per unit chlorophyll resulting from photoacclimation and photoinhibition (e.g., Behrenfeld et al., 1999). For all of these studies, the focus will be on developing relationships between physical/chemical environmental properties and corresponding physiological changes, such that the information gained can be readily applied to global physiological models. These efforts will require additional personnel and establishment of a laboratory separate from that used by the terrestrial plant research group (see NGTFC implementation plan). This ocean-dedicated facility is required because experiments conducted on terrestrial plants will unavoidably contaminate any phytoplankton studies on micronutrient limitation and because there is little overlap between laboratory equipment necessary for physiological studies on terrestrial and marine plants. An additional benefit of establishing a Goddard resident ocean laboratory is to provide a vehicle for collaborative studies with scientists outside NASA. The interaction between plant physiologists and remote sensing specialists can foster improved mechanistic models and thus enhance understanding of processes inherent in remote sensing data fields.

Development of physiological models is critical for improving our understanding of ocean carbon cycles. Such models yield common data fields with “coupled” models and thus provide a mechanism for evaluating consistencies and inconsistencies between these two approaches. Physiological models are also important because they are generally process-oriented. Unlike empirical models based on historical observations, process-oriented physiological models can be developed to forecast changes in the biological pump resulting from global climate change. Such forecasts may also be available from development of coupled models. As with the other model categories, continued development of physiological models and the resultant improved understanding of global changes in ocean carbon fluxes is critically dependent upon a commitment to the 20-year time series of ocean color data.

Empirical Production Models: Empirical primary production models are an area of expertise within the OCST. These models involve analysis of historical observational data sets to derived seasonal- or annual-scale estimates of ocean carbon fixation. Despite their lack of process-oriented relationships, these models provide important comparative information on distributions of ocean photosynthesis and can feed directly into estimates of particulate carbon flux to the sediments or the deep sea. The models depend critically on the spatial fields of satellite-derived chlorophyll biomass, and relate them empirically to associated physical fields such as mixed layer depth or the euphotic depth. Recent work has focused on defining regional differences in phytoplankton dynamics based on degrees of temporal variability. Some examples have included analyses of global ocean primary production computed from climatological CZCS data (Iverson et al., 2000). Activities are currently underway to intercompare several formulations from other institutions and to evaluate primary production from SeaWiFS. Future efforts involve use of MODIS ocean color data.

Coupled Models: Coupled models integrate physical and biogeochemical processes to produce a dynamical representation of phytoplankton and nutrient distributions. These models rely heavily on improved understanding of fundamental processes describing each model component (e.g., phytoplankton photosynthetic parameterizations, general ocean circulation fields, radiative fields, and loss terms) and on satellite data for constraint of output fields. Coupled models function as the basis for understanding complex interactions between processes involved in the carbon cycle and provide the greatest forecasting potential, especially when coupled to improved process-oriented variable parameterizations.

Coupled physical/biogeochemical modeling is not as mature as atmospheric and oceanic circulation modeling, but OCST staff are actively involved in this research area. In fact, OCST personnel are at the forefront of coupled three-dimensional models on coastal (Gregg and

Walsh, 1992), regional (Dutkiewicz et al., 2000), and global (Gregg, 2000) oceanic systems, as well as enhanced ecosystem models of the North Pacific (McClain et al., 1996) and western tropical Pacific (McClain et al., 1999), including explicit effects of iron limitation (Leonard et al., 1999). OCST personnel are actively involved in improving these models, utilizing a variety of approaches that vary in the processes involved and spatial domain. Specific coupled model activities underway include tropical, North Atlantic, and global models. Our multifaceted approach is entirely appropriate for this immature field of research and enables emphasis on different aspects of the problem, eventually leading to an improved understanding. Development of coupled models also provides a basis for integrating experience and knowledge gained from other efforts toward improved representations of underlying processes. OCST efforts in this area are intimately tied to satellite data for initialization, validation, and assimilation, which distinguish them from other national efforts. In this manner, the OCST coupled model development is viewed as complementary to the national plan and thus contributes to overall goals.

Ultimate research goals are to understand how climate change and the coupled ocean-atmosphere carbon system mutually interact. A major challenge of carbon cycle studies is to develop methods to incorporate data from ongoing observational programs, particularly from satellites, to monitor ocean biogeochemical cycling (Sarmiento and Armstrong, 1997), and eventually to forecast carbon distributions. The studies within this prospectus inherently contain this satellite data assimilation requirement within their objectives.

Expansion of OCST capabilities to further complement national goals in coupled modeling requires adaptation to carbon-specific outputs (instead of chlorophyll as presently constructed), incorporation of new carbon pathways (e.g., dissolved organic carbon), and better utilization of satellite data. A particularly new thrust is the extension of present models to the dissolved inorganic carbon cycle: the calculation of exchanges between organic requirements of CO_2 for carbon fixation and return via respiration. This process determines the equilibrium of CO_2 in the water column and its exchange potential with the atmosphere. This is an area of research that potentially couples the biological oceanic studies presently underway with the atmosphere and terrestrial components. Also required is the coupling of existing coupled oceanic models with atmospheric circulation models and land process models. Due to the complexity of the ocean carbon cycle and additional requirements for coupling with other models, the expansion activities of the OCST will require very large computational capability. We expect that because of the large number of state variables required for proper definition of carbon cycle processes, an order of magnitude larger capability is required than for current global coupled atmosphere/ocean models.

2.4.2 Development of New Algorithms to Improve Knowledge of Carbon Cycle Components and Variability and Air-Sea Gas Flux Using Satellite Observations

OCST activities in the area of algorithm development from satellite and other remote sensing data are extensive. Efforts fall into two major areas: 1) algorithms to improve and derive new estimates of carbon components from optical signals, and 2) algorithms to improve understanding of gas fluxes across the air-sea interface based on microwave signals.

Improving Estimates of Ocean Color

In order to extract useful information from ocean color sensor radiances, atmospheric and surface-reflected radiance must be removed. This requires theoretical atmospheric correction algorithms, usually with empirical components, for removal of scattered and reflected light, e.g., Rayleigh, aerosol, surface foam, sun glint, and reflected sky light radiances, and estimation of radiance lost due to absorbing gases and aerosols. While much work has been published on certain of these corrections, several corrections remain approximate at best and must be improved from both a theoretical and observational standpoint. From estimates of water-leaving radiances, algorithms must be derived which relate these radiances to subsurface constituents and optical properties, e.g., chlorophyll-a. Bio-optical algorithms for these properties are classified as empirical or semi-analytical. Either way, all are based on observations of some kind and attempt to encompass the broad range of biological variability in optical properties. Understanding the underlying theoretical and observation basis for both atmospheric correction and bio-optical algorithms is critical for understanding the error in global carbon budgets.

Retrieval of Optical Properties of Carbon-Containing Constituents

Retrieval of inherent optical properties (IOP's) of the ocean is a new approach in satellite determination of oceanic constituents and their concentrations. Especially important are the inherent optical properties of carbon-containing/fixing phytoplankton, CDOM-detritus, and total constituent backscattering (including coccoliths/coccolithophores) in the upper mixed layer of the ocean. These IOP's can be converted to constituent concentrations or, alternatively, into units of carbon concentration. Refinement of the global oceanic carbon budget requires the assessment of carbon from all sources. A major objective of this work is to develop physical models or methodologies to allow routine, accurate retrieval of oceanic inherent optical properties from satellite remote sensing reflectances and their conversion to molar carbon. The three above carbon sources are sometimes labeled phytoplankton carbon, DOM carbon, and calcite carbon, especially outside coastal regions where the carbon partitioning is more predictable.

While much research effort has been directed toward biologically active constituents, it is important to note that DOC in seawater represents one of the largest reservoirs of reduced carbon on the Earth's surface (Hedges and Farrington, 1993). There is as much carbon in dissolved organic material in the oceans as there is CO_2 in the atmosphere (Hedges, 1993). Thus, improved knowledge of the global carbon cycle requires that we study the entire oceanic carbon pool, including the production, distribution, transport and fate of both particulate and dissolved organic material together with biologically active constituents.

Empirical radiance ratio algorithms (Gordon et al., 1983; O'Reilly et al., 1998) which form the basis for widely used chlorophyll retrieval from satellite imagery have limitations that restrict their utility. These algorithms, as applied to satellite ocean color data, provide only an estimate of the chlorophyll pigment and do not, and cannot, properly account for the absorption and backscattering of other carbon-containing constituents such as CDOM. Recently, oceanic radiative transfer methods have been successfully demonstrated to simultaneous retrieve the three principal IOP's of the ocean from satellite data: CDOM-detritus absorption coefficient, phytoplankton absorption coefficient, and total constituent backscattering (TCB) coefficient (Hoge et al., 1999).

The retrieved IOP's are converted to molar carbon concentration by algorithms that are yet to be developed. However, a foundation has been built during the last few years, and requires further development by the OCST. Specifically, (1) the phytoplankton absorption coefficient IOP can be used to derive elemental carbon estimates using the method of Lee et al. (1996), (2) the CDOM-detritus absorption coefficient IOP is related to DOC (Vodacek et al., 1995), and (3) total constituent backscattering may ultimately be used for retrieval of coccolith concentration and/or calcite carbon (Balch et al., 1992). Future research efforts must address improved estimation of carbon from these IOP's. The phytoplankton absorption coefficient may also permit improvement of primary production estimates (Lee et al., 1996). While the Vodacek et al. (1995) carbon vs. CDOM absorption contained no corrections or parameterizations for surface layer photodegradation, their initial findings are suitable for preliminary algorithm use. More intense research efforts are recommended to adapt the coccolithophore empirical algorithm (Balch et al., 1991) for use with the radiative transfer-derived total constituent backscatter IOP product.

Much work remains to be done, since this new oceanic radiative transfer methodology propagates errors in ways that are significantly different from the older band-ratio phytoplankton chlorophyll pigment algorithms (Hoge and Lyon, 1996). Also, about 85% to 90% of the atmospheric reflectance must be removed from satellite ocean color data to allow observations of oceanic properties. Spectral radiance (or reflectance) uncertainty can lead to significant errors in the retrieved inherent optical properties, that in turn provide information on the carbon concentration of the constituents (Hoge and Lyon, 1996). Thus, new and more robust atmospheric radiative transfer methods must be developed in order to take advantage of the concurrent new oceanic radiative transfer advancements.

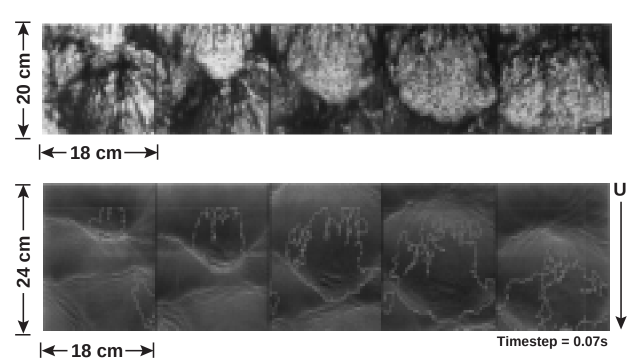

Figure 5. Image of fractional areas of whitecaps observed in an infrared image (top), and computed as the slope of the surface roughness. (Results of FEDS.98 Courtesy of W. Asher, UW/APL, J. Klinke, SIO, and S. Long (GSFC/WFF)

Very robust airborne methods have recently been established for development of oceanic and atmospheric radiative transfer algorithms. Airborne active (laser) and passive (solar) methods were pioneered by OCST members in 1986 (Hoge et al., 1986a; Hoge et al., 1986b). Recently, forward oceanic radiance modeling and its comparison with airborne active-passive data were used to validate the Gordon et al. (1988) semi-analytic radiance model of ocean color and an inherent optical property model for the phytoplankton absorption coefficient (Hoge et al., 1995). Subsequent to this airborne forward-modeling field validation, the semi-analytic model was used to theoretically demonstrate a well-conditioned retrieval of IOP's (Hoge and Lyon, 1996) from oceanic reflectance data. More recently, the model was used to retrieve the three principal IOP's from airborne oceanic reflectance data (Hoge et al., 1999). Atmospheric correction of a single satellite image has shown that it is feasible to retrieve inherent optical properties over vast areas of the ocean (Hoge et al., 1999). A low-altitude airborne active-passive underflight of the satellite validated that both the oceanic radiative transfer model inversion and the atmospheric correction were accurate for this single image. General atmospheric correction methods currently in use need further refinement and development before radiative transfer model inversion methods can be applied to global satellite data sets. The use of low- altitude airborne oceanic radiometers have now demonstrated that they can provide data for both (a) oceanic radiative transfer inversion algorithm development and (b) atmospheric correction algorithm development.

Algorithms for Gas Flux Estimation Across the Air-Sea Interface

Recent wave tank studies at the Observational Sciences Branch indicate that gas flux across the air-sea interface can be parameterized better with the surface roughness measures. This represents a breakthrough from the traditional wind-based algorithms. Yet the study is still incomplete, for the role of whitecaps and bubbles are not fully examined. As all the parameters for the air-sea flux algorithm can be measured by microwave sensors such as radiometers and scatterometers there is high potential that a better integrated algorithm can be developed to quantify the air-sea mass flux based on data from microwave remote sensing instruments. Coupled with observations of the CO_2 concentration, the new algorithm for gas flux could make our understanding of the carbon cycle much more quantitative.

2.4.3 Analysis of Spatial and Temporal Variability in Satellite Data

The primary purpose of a 20-year time series of ocean color data is to detect change. This is central to the activities of the national carbon plan and a goal in which OCST must play a leading role. Past activities of the OCST have emphasized regional analysis and spatial variability with the CZCS. This primarily reflects the limitations of sampling in the CZCS archive that preclude extensive analysis of temporal variability. OCST efforts in the analysis of regional variability have included the eastern tropical Atlantic (Monger et al., 1997), Arabian Sea (Banse and McClain, 1986; Brock et al., 1991), North Atlantic (McClain and Firestone, 1993), Southern Ocean (Comiso et al., 1993; McClain et al., 1991), equatorial Pacific (Feldman et al., 1984; Murtugudde et al., 1999), the tropical and subtropical Atlantic (Signorini et al., 1999), and the classification of global ocean color provinces (Esaias et al., 2000), among others. Nevertheless, analyses of interannual variability of selected regions have been successfully pursued by the OCST (e.g., Brock and McClain, 1992; Leonard and McClain, 1996). While these efforts are extensive, future challenges associated with the 20-year time series must be met.

3. PROGRAM INTEGRATION

The scope of the global carbon cycle problem transcends typical scales of disciplinary studies and presents a unique opportunity for the Goddard OCST. The OCST provides a coordination forum to improve collaboration with existing activities within the OCST, with our colleagues in the Earth Science Directorate, and with the external community. The OCST will actively pursue collaborative opportunities to improve our understanding of the ocean carbon cycle through the use of remote sensing data.

Within the OCST, we intend to integrate improved CDOM algorithms by Hoge, with primary production by Esaias and Behrenfeld to help understand the pathways of fixed organic carbon in the oceans. Combining this information with the coupled models of Gregg, McClain, and Busalacchi, can provide important new insights into carbon cycling through very poorly understood pathways, its magnitude, and importance in ocean carbon cycling. Coupled with models of inorganic carbon pathways, these efforts can help refine estimates of the partial pressure of CO_2 in the water column.

SEI data can resolve aliasing of coastal observations due to tidal and river influences. This information can help coupled and empirical models improve the representation of short-term variability. Better knowledge of this short-term variability, through the combined information from an observing system and models, will enable us to determine if the bi-daily sampling provided by polar orbiter satellites is adequate for understanding ocean carbon dynamics or whether higher frequency information is required, such as from multiple low-Earth orbit satellites in various inclination and crossing times or geostationary orbits, or combinations. Mission simulation analyses can help resolve issues of orbit selection.

The 20-year time series of ocean color observations heavily supports the spatial and temporal variability analysis function of the OCST. Furthermore, it leads to inferences of processes affecting this variability that can be used to improve the empirical and coupled models, and improve the capability for forecasting.

Basic science efforts within the OCST not only refine the fundamental principles and processes involved in the ocean carbon cycle, but also support new mission development. Wave tank analyses of surface roughness and the influence of surfactants can lead to new remote sensing technologies for observing the key processes at work in air/sea gas (CO_2) exchange. Laboratory analyses of phytoplankton physiology will enhance our understanding of variability in carbon fixation rates. Electromagnetic impulses can be tested in this laboratory to derive possible remote sensing technologies.

Perhaps more important, and more relevant to global carbon cycle analyses, is the prospect of OCST activities to provide opportunities for interdisciplinary efforts within the GSFC Earth Sciences Directorate. These studies can accelerate our understanding of carbon pathways in the oceans and how they interact with atmospheric and terrestrial processes. This information, in turn, can be implemented into coupled ocean models, as well as coupled land/ocean/atmosphere models to provide an understanding on feedback mechanisms and may potentially yield future forecast capabilities. We intend to emphasize four general areas of interdisciplinary research, each intimately related to remote sensing observations:

1) monitor and evaluate biospheric change;

2) develop and apply new estimates of global biospheric primary production;

3) evaluate the effects of cross-disciplinary processes observed from remote sensing.

4) combine atmospheric, terrestrial, and oceanic models to evaluate the processes and effects of global carbon cycling, its potential impact on climate, and to predict the effects due to anthropogenically induced changes.

1) Monitor and evaluate biospheric change.

One of the most important applications of remote sensing data is the analysis of temporal changes directly observed in the data. The 18-year time series of AVHRR terrestrial biomass indices is an invaluable source of temporal variability observations for the land community. The proposed 20-year time series of ocean color in the present effort would fill a similar role for oceanic research. Active involvement in the development and operation of a global atmospheric CO_2 observational capability would fill the gap in our satellite observations. The combined observations of future integrated missions such as EOS Terra and Aqua, as well as NPP and NPOESS, provide an unprecedented and previously unattainable direct remote observation of global biospheric change.

2) Develop and apply new estimates of global biospheric primary production.

Recent advances in the estimation of primary production from satellite data, on both land and oceans (e.g., Field et al., 1998) emphasize the importance of satellite data for improving our understanding of global biospheric carbon fixation. SeaWiFS is the first satellite that can provide high-quality, high-resolution biomass data from both terrestrial and oceanic sources from the same platform. This is an unprecedented opportunity to determine primary production simultaneously on land and in the ocean, and combine them into a single coherent global estimate. Continued observations will be available from MODIS on both EOS Terra and Aqua, and hopefully into the future. NGTFC members bring together sophistication in primary production analyses along with the intricacies of satellite observations that can enable new and improved estimates of global primary production.

3) Evaluate the effects of cross-disciplinary processes observed from remote sensing.

The more we learn about carbon cycling processes within disciplines, the more it becomes apparent that we cannot understand them without help from other disciplines. Many of these cross-disciplinary processes are observable from space. For example, rivers represent the export of terrigenous organic matter and an import to ocean coastal regions. The loss of carbon from the land must be accounted for in global carbon budgets, as well as its pathways in the oceanic domain. River influences are readily apparent from remote sensing platforms. Recent analyses of oceanic phytoplankton have emphasized the importance of iron as a limiting nutrient in some parts of the oceans. In these areas, the major source of input of iron to the oceans is derived from land sources, and transported to the oceans through the atmosphere. Analyses and models of photosynthesis, primary production, and carbon cycling can contain a large amount of unexplained variance if this process is not accounted for. Aerosols, some of which may contain iron, are readily observable in satellite imagery. This can provide an opportunity for a multidisciplinary effort to understand the sources, transport, and impacts of iron derived from land and deposited in the oceans. The NGTFC is poised to make inroads into this important component of global carbon dynamics as an interdisciplinary team effort.

4) Combine atmospheric, terrestrial, and oceanic models to evaluate the processes and effects of global carbon cycling, its potential impact on climate, and to predict the effects due to anthropogenically induced changes.

NASA/GSFC supports an extensive fleet of large-scale modeling efforts in several different disciplines. These efforts extend from highly organized projects, like the

NASA Seasonal-to-Interannual Prediction Project (NSIPP) to multi-investigator, multidisciplinary efforts, to smaller efforts with a few investigators working on disciplinary concepts. One of the major goals of the NGTFC is to unite these efforts to construct models representing multiple aspects of the global carbon cycle, emphasizing the interdisciplinary nature of the problem, and emphasizing coupling between these disciplines. The overall goal may be several models, but the unifying theme is to understand and predict global carbon dynamics on seasonal to interannual to decadal to climate change time scales, with models intricately linked to remote sensing data.

In this objective we intend to link with ongoing GSFC efforts to produce enhanced representations of the global biosphere and the carbon cycle. On seasonal-to-interdecadal time scales, we will couple the ocean general circulation model (OGCM) of NSIPP with an ocean general biogeochemical/radiative model (OGBM), eventually coupling with the coupled atmosphere/ocean model of NSIPP. The land surface hydrological model of NSIPP will be enhanced with the Simple Biosphere (SiB2) model and coupled with the NSIPP atmospheric GCM as well as the NASA/NCAR general circulation/transport model. On decadal-to-climate change time scales, we will link the SiB2 and the OGBM/OGCM to the GISS climate model of the Earth system. This sequence of coupled models linked to satellite data fields will require substantial development time, but we can envision a satellite system assimilation forecast model that can evaluate and predict changes in anthropogenic forcing of carbon related processes with near-term changes in carbon cycling, which may have important effects on climate and weather systems. In the long term, the processes more fully understood by the coupling of these models will enable improvement of predictions of future atmospheric carbon loading and the consequences. This approach of coupled interdisciplinary models with satellite data in assimilation/forecast mode, as well as historical reconstructive mode, will provide a fuller understanding of the global carbon cycle, the processes affecting it, and the implications of changes. This will contribute a satellite-based scientific application to the goals of the U.S. Carbon Cycle Program.

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APPENDIX—OCST TEAM MEMBERS, ACTIVITIES AND RESPONSIBILITIES

The OCST includes 10 active members, whose scientific interests range from small-scale analyses of fundamental phytoplankton physiology, to regional scale ocean numerical physical/biological modeling, to regional and global scale algorithm development, to global primary production and global ocean numerical physical/ biogeochemical modeling. It is a diverse group representing 4 distinct organizational units at GSFC. Project and mission responsibilities are a primary effort by the OCST, who serve on numerous mission science teams, and also provide managerial responsibilities on several missions. These activities form the core of a world-class ocean color team at GSFC. For this team to take on the additional responsibility of a carbon cycle effort, personnel expansion is required, especially in the areas of mission oversight, ocean data processing, and development of new technologies.

Scientific Activities	NASA Mission Activities
<u>Mike Behrenfeld (Oceans and Ice Branch)</u>	
global ocean primary production	SeaWiFS science team
analysis of iron effects on marine phytoplankton	
analysis of marine phytoplankton photosynthetic physiology	
<u>Wayne Esaias (Oceans and Ice Branch)</u>	
global ocean primary production	MODIS Ocean Team Leader
mission/sensor analysis	SeaWiFS consultant
	SEI Principal Investigator
	NPP advisor
	NPOESS advisor
	MLL science team
<u>Gene Feldman (Global Change Data Center)</u>	
scientific data processing, design, and implementation	SeaWiFS Data Processing Manager
data analysis	SIMBIOS Data Processing Manager
educational outreach	SEI Data Processing Manager
<u>Watson Gregg (Oceans and Ice Branch)</u>	Ocean Carbon Science Team Leader
global ocean coupled physical/biogeochemical/ radiative modeling	SeaWiFS science team
ocean color data and in situ merging algorithms	SIMBIOS science team
mission simulation and analysis	MLL science team

Frank Hoge (Observational Sciences Branch)

algorithm development for ocean color satellites	AOL team leader
algorithm development for LIDAR	MODIS science team
radiative transfer modeling of oceanic inherent optical properties	MLL science team
	OCTS science team
	POLDER science team
	SIMBIOS science team

Stan Hooker (Oceans and Ice Branch)

mission validation	SeaWiFS Project
development of in situ radiometers	
field studies in support of ocean color missions	

Norden Huang (Oceans and Ice Branch)

air/sea interaction
gas flux exchange

Norman Kuring (Global Change Data Center)

scientific data processing and analysis	SeaWiFS Project
	SIMBIOS Project

Steven Long (Observational Sciences Branch)

air/sea interaction
gas flux exchange

Charles McClain (SeaWiFS/SIMBIOS Project Office)

coupled physical/biological modeling of the tropical oceans	SeaWiFS Project Manager
iron-based ecosystem modeling	SeaWiFS Project Scientist
analysis of spatial variability of ocean color	SeaWiFS Cal/Val Manager
	SIMBIOS Project Manager
	SeaWiFS science team
	OCTS science team
	POLDER science team
	GLI science team

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13. ABSTRACT *(Maximum 200 words)*

There are increasing concerns that anthropogenic inputs of carbon dioxide into the Earth system have the potential for climate change. In response to these concerns, the GSFC Laboratory for Hydrospheric Processes has formed the Ocean Carbon Science Team (OCST) to contribute to greater understanding of the global ocean carbon cycle. The overall goals of the OCST are to: 1) detect changes in biological components of the ocean carbon cycle through remote sensing of bio-optical properties, 2) refine understanding of ocean carbon uptake and sequestration through application of basic research results, new satellite algorithms, and improved model parameterizations, 3) develop and implement new sensors providing critical missing environmental information related to the oceanic carbon cycle and the flux of CO_2 across the air-sea interface.

The specific objectives of the OCST are to: 1) establish a 20-year time series of ocean color, 2) develop new remote sensing technologies, 3) validate ocean remote sensing observations, 4) conduct ocean carbon cycle scientific investigations directly related to remote sensing data, emphasizing physiological, empirical and coupled physical/biological models, satellite algorithm development and improvement, and analysis of satellite data sets.

These research and mission objectives are intended to improve our understanding of global ocean carbon cycling and contribute to national goals by maximizing the use of remote sensing data.

14. SUBJECT TERMS

Global ocean carbon cycle; ocean carbon science team; NASA/GSFC Task Force for Carbon.

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